Groundwater Flow Systems and Recharge in the Buena Vista Basin, *Portage and Wood Counties, Wisconsin*

Kenneth R. Bradbury
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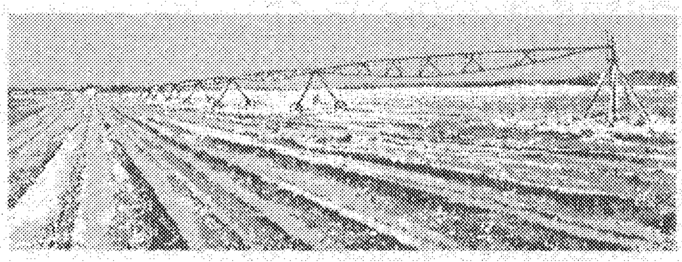

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FIGURES

TABLES

GROUNDWATER FLOW SYSTEMS AND RECHARGE IN THE BUENA VISTA BASIN,

PORTAGE AND WOOD COUNTIES, WISCONSIN

Kenneth R. Bradbury, John M. Faustini, and Mary W. Stoertz

ABSTRACT

The Buena Vista groundwater basin covers about 440 km^2 in Portage and Wood Counties, Wisconsin, and is representative of other groundwater basins in the central sand plain of Wisconsin. The Buena Vista basin is a self-contained groundwater unit, bounded on the east by the regional groundwater divide between the Wolf and Wisconsin River basins, on the west by the Wisconsin River, and on the north and south by flow-line boundaries. Most groundwater flow paths in the basin are short, from local recharge to local discharge areas. The average linear horizontal groundwater velocity is about 0.3 m/day.

Groundwater recharge in the Buena Vista basin occurs over four different types of recharge areas. We based an interpretative map of groundwater recharge and discharge areas in the basin on field observations of vertical gradients, streamflow data, and water-table configuration, fluctuations, and depth. Analyses of environmental tritium in groundwater helped confirm the recharge and discharge zones.

We also used a computer-aided mapping technique (based on a water balance) and the water-table configuration to map recharge and discharge in the basin. This technique produced a map similar to the field map and can easily be applied to similar hydrogeologic settings.

Results of this study should be useful to planners, water managers, and regulatory officials who wish to protect the groundwater resources of the central sand plain. Techniques described in this report should be useful in other areas having shallow, unconfined aquifers.

ACKNOWLEDGMENTS

We acknowledge the cooperation of the landowners in central Wisconsin who allowed the installation of wells and piezometers on their property. Richelle Allen conducted and analyzed the piezometer tests that are listed in the appendix. Michael Lemcke and Randy Boness assisted with the field work associated with this project. Mary Anderson, Lee Clayton, Thomas Osborne, and Ronald Hennings reviewed the manuscript of this report and provided valuable comments.

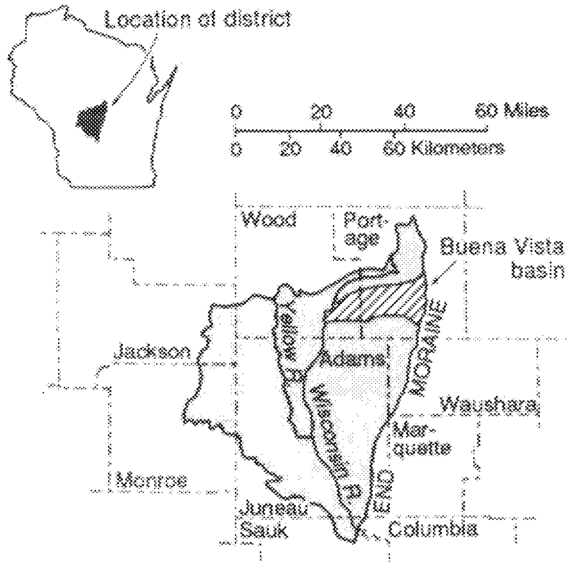


Figure 1. *Location of the central sand plain (shaded area) of Wisconsin.*

INTRODUCTION

The central sand plain of Wisconsin is an important and highly productive agricultural region that covers parts of Portage, Wood, Adams, Waushara, Juneau, Monroe, and Jackson Counties (fig. 1). In this area, permeable, water-bearing sand and gravel overlies less permeable Cambrian sandstone or Precambrian rock and forms an important shallow, unconfined aquifer (Zaporozec and Cotter, 1985). A combination of irrigation, liberal use of agricultural chemicals, highly permeable soils, and a shallow water table has resulted in a significant potential for groundwater contamination; the demand for groundwater for irrigation, as well as other uses, is increasing rapidly. Much of central Wisconsin rates as "most susceptible to contamination" on a recent map of groundwater contamination susceptibility (Wisconsin Department of Natural Resources, 1987).

Although groundwater quality in the sand plain is generally good (Hindall, 1978), contaminants have been reported in some drinking-water wells (Saffigna and Keeney, 1977; Manser, 1983), and groundwater contamination has become a cause for serious concern. Protecting groundwater requires a thorough understanding of the factors that control groundwater movement and chemistry in the region. To prevent serious degradation of this resource through the current period of rapid development and into the future, careful management based on a sound understanding of the groundwater flow system will be essential.

From 1982 through 1988 staff of the Wisconsin Geological and Natural History Survey conducted research about the geology, hydrogeology, and groundwater flow systems in central Wisconsin, with a focus on groundwater recharge. In this report we summarize the results of an intensive study of a single groundwater basin within the central sand plain. The methodology, results, and conclusions of this study can be generalized to larger areas of the sand plain and to other areas of Wisconsin having similar hydrogeologic settings. Faustini (1985), Stoertz (1985, 1989), Zheng (1988), Stoertz and Bradbury (1989), and Bradbury (1991) have reported major parts of this work. This report represents a synthesis and summary of their findings.

Purpose

In this report we present a detailed analysis of groundwater movement and the spatial distribution of groundwater recharge and discharge in part of central Wisconsin. The report also provides estimates of groundwater flow rates, aquifer parameters, and groundwater recharge rates. The goal of this study was to determine the patterns of groundwater movement, recharge, and discharge in the study area.

The primary objectives were

- to determine whether most groundwater flow in the study area is part of a single regional flow system;
- to delineate a self-contained groundwater basin that is characteristic of other basins in the central sand plain, and to identify boundaries of this basin;

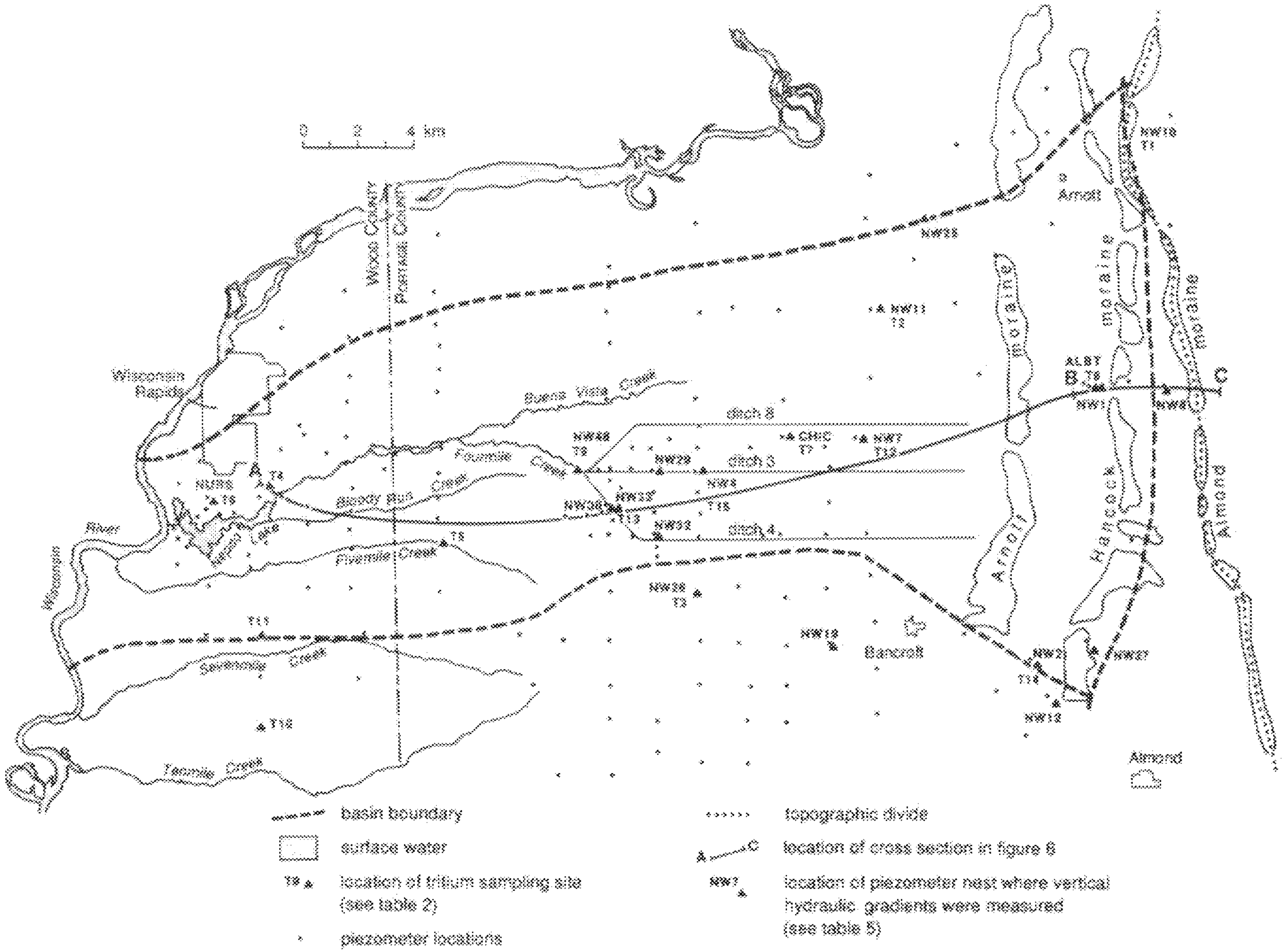


Figure 2. *Location and major features of the Buena Vista basin, showing water-level measurement network, locations of piezometer nests, and locations of tritium sampling sites.*

- to determine the lengths of groundwater flow paths and rates of groundwater flow within the basin;
- to map the distribution of groundwater recharge areas and groundwater discharge areas in the basin; and
- to estimate groundwater recharge rates within the basin.

Although concern over the potential for groundwater contamination in central Wisconsin motivated this report, we do not directly discuss groundwater quality. Instead, we describe the groundwater flow system to provide the information needed to predict the movement of contaminants in groundwater and to assess the techniques and effort required to obtain such information.

Study area

Our study area covers approximately 780 km^2 in southeastern Wood and southern Portage Counties, Wisconsin (fig. 2). Within the study area, a groundwater basin of approximately 440 km^2 was delineated; it is here called the Buena Vista groundwater basin.

The east boundary of the Buena Vista groundwater basin is the regional groundwater divide between the Wisconsin and the Wolf

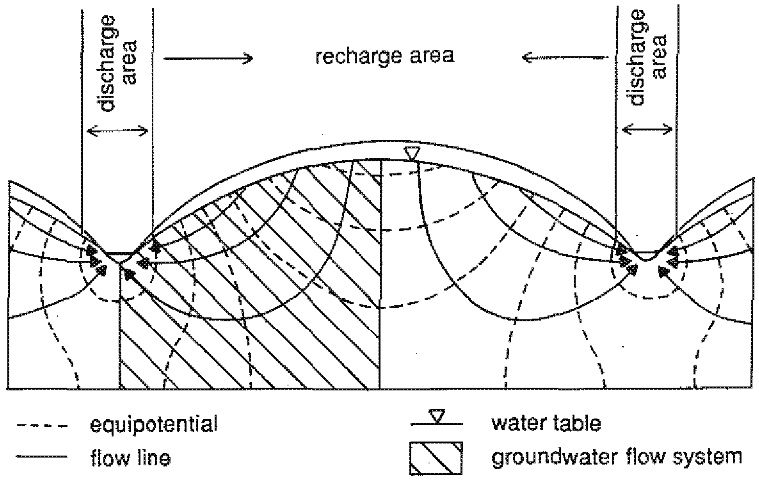


Figure 3. *Cross section through a simple hypothetical groundwater basin.*

River basins; the regional groundwater divide lies slightly west of the topographic divide between the Wolf and Wisconsin River basins. The west boundary of the Buena Vista basin is the Wisconsin River, the regional groundwater discharge boundary. The northern and southern boundaries of the Buena Vista groundwater basin are formed by flow lines corresponding to divides between the Wisconsin River and Buena Vista and Fourmile Creeks and between Fourmile and Tenmile Creeks, respectively.

Precipitation

The average annual precipitation in the study area, based on the period 1941 through 1970, is 79.0 cm at Wisconsin Rapids. Approximately 60 percent of the total annual precipitation occurs during the growing season (May through September). Precipitation during the winter occurs chiefly as snow, which accumulates on the ground from about mid-November until the beginning of spring thaw in March or early April.

Topography

The Buena Vista basin, like most of the central sand plain, has little topographic relief except for a series of north-south trending end moraines (fig. 2), which form the eastern boundary of the sand plain, and a few sandstone mounds that protrude through the unlithified sediment. The moraines take the form of linear, but highly irregular, hummocky ridges. The easternmost of these ridges is the Almond moraine (Clayton, 1986), which rises 15 to 50 m above the surrounding outwash and till and forms the topographic divide between the Wisconsin and the Wolf and Waupaca River basins. Immediately west is the Hancock moraine, equally high but with gaps cut through by meltwater streams. Between the Hancock and Almond moraines is a pitted outwash plain.

Terminology

According to conventional usage, groundwater *recharge* is the addition of water to the saturated zone, and groundwater *discharge* is the removal of water from the saturated zone. These terms can be used to refer to quantities of water as well as processes. Recharge occurs in response to infiltrating rainfall, infiltrating snowmelt, leakage from lakes and streams, or artificial recharge, such as irrigation or wastewater infiltration. Evaporation, plant transpiration, pumping, and flow to lakes and streams are common mechanisms of groundwater discharge.

Given these definitions, recharge and discharge can occur simultaneously at a specific site. For example, plants may withdraw water from below the water table at the same time that

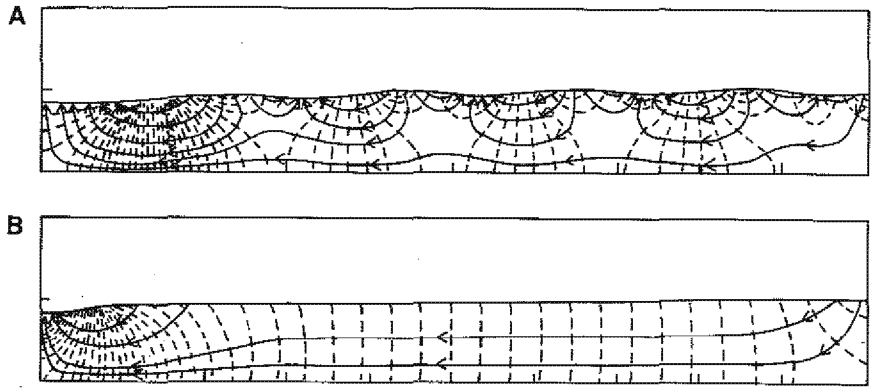


Figure 4. *Cross sections through two hypothetical groundwater basins, showing the effect of different water-table configurations (from Freeze and Cherry, 1979). A: hummocky water table; B: flat, gently sloping water table.*

rainfall adds water above the water table. An irrigation well can remove groundwater from below the water table at the same time that the irrigation adds water above the water table. Recharge and discharge can also occur alternately at a given site, as may be the case when a dry period, which causes upward movement of water to the unsaturated zone, is followed by a large rainstorm, which creates recharge.

It is difficult to distinguish all the recharge and discharge fluxes that occur during a given time period. Therefore, for the purposes of this report, these fluxes are expressed as a net flux that takes into account all gains and losses of water over a specified time period, typically one year. An area where the recharge process dominates (as judged by the frequency of occurrence of downward hydraulic gradients) is called a *recharge area;* an area where the discharge process dominates is called a *discharge area.* This usage follows Freeze and Cherry (1979, p. 194), who defined a recharge area as "...that portion of the drainage basin in which the net saturated flow of groundwater is directed away from the water table. In a recharge area, there is a component to the direction of groundwater flow near the surface that is downward." Similarly, a discharge area is "...that portion of a drainage basin in which the net saturated flow of groundwater is directed toward the water table. In a discharge area, there is a component to the direction of groundwater flow near the surface that is upward." These definitions, in referring to a *net* flow of water, implicitly recognize the transient nature of groundwater systems.

METHODOLOGY

Conceptual model

In this report we describe groundwater flow, recharge, and discharge within the framework of a conceptual model of groundwater flow systems. The flow system model was first introduced by Hubbert (1940), expanded and placed into the conceptual framework of groundwater basins by Toth (1962, 1963), and further refined and developed by Freeze and Witherspoon (1966, 1967, 1968).

Figure 3 illustrates several features that are characteristic of natural groundwater flow systems. First, there is a downward component of flow at recharge areas and an upward component of flow at discharge areas. Second, the water table is generally deep in recharge areas and shallow in discharge areas. Third, discharge areas occupy a smaller part of the basin than recharge areas.

The configuration of the water table in humid regions tends to mimic surface topography (Toth, 1963; Freeze and Cherry, 1979); figure 4 illustrates the influence of topography on the development of groundwater flow systems. The complex groundwater basin depicted in figure 4a, which incorporates several flow systems of different scales, results from an upper boundary consisting of a sloping, gently undulating water table; the other boundary conditions are similar to those in figure 3. Figure 4b shows the groundwater flow pattern for a basin having the same overall relief as that in figure 4a, but possessing a flat, gently sloping water table rather than an undulating one. In this case, only a single regional flow system develops.

Monitoring network

The subdued topography of the central sand plain has made it unclear whether groundwater flow systems of various sizes occur there. The groundwater monitoring network was designed to determine whether all groundwater flow in the study area is part of a single regional flow system or whether smaller flow systems exist.

The configuration of the water table, which represents the hydraulic head distribution at the upper surface of the saturated zone, is the most useful information generally available for determining groundwater flow directions in an unconfined aquifer. (Due to the coarseness of the sand, the capillary fringe is negligible in the Buena Vista basin.) Information about the variation of hydraulic head with depth also helps identify the vertical movement of groundwater. To obtain this information, we installed 128 piezometers in the study area. In addition, we monitored groundwater levels in 120 existing piezometers and surface-water levels at 28 control points in the drainage ditches of the Buena Vista marsh area.

Figure 2 shows the locations of the piezometers. Piezometers consisted of 3.2-cm diameter PVC or galvanized steel standpipes with commercially slotted PVC screens 1 m in length. We installed all piezometers using solid or hollow-stem augers without the addition of any drilling fluids and developed them by pumping and surging, again without the addition of any fluids. Most new piezometers installed for this study were located in the eastern two-thirds of the study area, where existing piezometers were scarce. In the western third of the basin, existing piezometers (mostly installed by Karnauskas, 1977) were the major source of head data. We concentrated drilling efforts in the vicinity of the regional groundwater divide (based on the water-table map of Karnauskas, 1977) to determine the location of the divide more accurately and in the central part of the basin to determine the effect of the drainage ditches on groundwater movement.

We installed piezometer nests (two or more piezometers screened to different depths at the same location) in the vicinity of the regional groundwater divide and adjacent to drainage ditches in the central marsh area to determine whether vertical hydraulic gradients occur in these areas. Shallow piezometers were installed between the ditches to determine whether significant groundwater divides occur there.

The final piezometer network, including existing and new wells, consisted of 236 piezometers at 176 sites, 88 of which were constructed as nests at 28 locations.

The piezometer network provided several types of information. Bimonthly measurements of water levels in the entire network during 1983 and 1984 gave the configuration of the water table and helped determine seasonal variations in the pattern of groundwater movement. Head measurements at piezometer nests were used to determine vertical hydraulic gradients. Piezometer slug tests conducted at many sites measured *in situ* horizontal hydraulic conductivity (appendix). We collected groundwater samples from piezometers at selected sites for analysis of tritium content. In addition, we measured the discharge of several shallow drainage ditches.

Regional hydrogeology

Hydrogeologic units

The hydrogeology of the Buena Vista basin is typical of the sand plain region. It is characterized by a thick layer of highly permeable unlithified sediment overlying less permeable rock; the sediment makes up a shallow unconfined aquifer. The geology of the study area was described by Holt (1965), Weeks and Stangland (1971), Clayton (1986), Brown and Greenberg (1986), Brownell (1986), Greenberg and Brown (1986), and Batten (1989).

Precambrian rock

Precambrian igneous and metamorphic rock underlies the entire study area, but rock is exposed at the land surface within the study area at only a few places along the Wisconsin River. The igneous and metamorphic rock lies directly under sand and gravel in the northern part of the study area; south of the study area, this rock lies beneath sandstone (Weeks and Stangland, 1971; Holt, 1965; Clayton, 1986). The Precambrian rock has a lower hydraulic conductivity than the overlying sand and gravel and probably constitutes a lower boundary to groundwater flow systems in the sand and gravel. We do not discuss groundwater movement in the Precambrian material in this report.

Cambrian rock

Sandstone of Late Cambrian age overlies the Precambrian rock in the southern part of the study area. The sandstone consists predominantly of medium to coarse silica sand, which is uniform in composition but highly variable in degree of cementation (Holt, 1965). Beneath the sandstone a relatively thin layer of clayey hillslope deposits blankets the underlying Precambrian rock; it probably was derived from the weathering of the rock. The hydraulic conductivity of the sandstone is much less than that of the overlying sand, and the hydraulic conductivity contrast between the sand and the sandstone is probably great enough that the sandstone has an inconsequential effect on the hydrogeology of the sand and gravel.

The surface of the sandstone is irregular. Steep-sided sandstone mounds and ridges project through the outwash in places where well cemented sandstone caprock protects the more weakly cemented sandstone beneath; undoubtedly, there are other mounds and ridges buried beneath the sand. These mounds affect groundwater flow in places, but they are too small to have a significant effect on the regional pattern of flow in the Buena Vista groundwater basin. Weeks and others (1965) noted that a north-south trending buried sandstone ridge in the Little Plover River basin acts as a barrier to groundwater flow there.

Pleistocene and Holocene material

Unlithified Pleistocene and Holocene material as thick as 45 m blankets much of the study area. This material consists of sandy till, stream sediment, and lake sediment, mapped in roughly that sequence from east to west. These sediments are included in the Horicon Formation (Mickelson and others, 1984). Clayton (1986) and Brownell (1986) described the origin and characteristics of these units and presented detailed cross sections of subsurface stratigraphy.

The stream sediment and lake sediment are the most extensive and hydrogeologically important units in the study area. Both consist of well sorted sand and gravel. The median grain size of the sand ranges from about 0.25 to 1 mm. Brownell (1986) distinguished three stratigraphic zones within the sand and gravel on the basis of textural composition, but the differences between these textural zones are relatively subtle, and the sand and gravel is considered to constitute a single hydrostratigraphic unit.

The moraines at the eastern end of the study area are composed of sandy till of the Mapleview and Keene Members of the Horicon Formation (Clayton, 1986). This till is similar in composition to the sand and gravel of the stream and lake sediment but is more poorly sorted. The till is predominantly composed of sand, but also contains significant quantities of

Table 1. *Summary of hydraulic characteristics of stream and lake sediment in the Buena Vista basin.*

Test type	Number of tests	Hydraulic conductivity (m/s x 10^{-4}) Geometric mean	Range	Source(s)
Pumping	10	7.3	6.5–17.9	Bradbury & Rothschild (1985); Holt (1965); Weeks (1969); Weeks & Stangland (1971); Karnauskas (1977)
Specific capacity	266	6.4	2.0–500.0	Bradbury & Rothschild (1985); Rothschild (1982)
Piezometer (slug test)	44	2.2	0.03–9.5	Appendix (this report)
Permeameter	7	1.5	1.2–8.8	Stoertz (1985)

silt and clay and large amounts of gravel, which do not affect the slope of the water table in the vicinity of the moraines (Weeks and others, 1965). Apparently, the moraines are underlain by stream sediment and have little effect on the water-table slope because, in general, they lie above the water table. Nelson (1978) reached this conclusion relying principally on well logs; the work of Masterpole (1983) and Brownell (1986) also supports this conclusion, as do Clayton's (1986) cross sections.

Offshore sediment that was deposited in proglacial lakes occurs at the surface in the extreme southwestern corner of the study area adjacent to the Wisconsin River; it occurs in the subsurface over much of the rest of the study area. This sediment consists predominantly of well sorted medium to fine and silty sand (Weeks and Stangland, 1971; Clayton, 1986). A fine-grained layer of lake sediment (the New Rome Member of the Big Flats Formation) extends east of this outcrop area and is present in the subsurface over a large part of the central sand plain (Brownell, 1986). However, within the Buena Vista groundwater basin this fine-grained sediment occurs as a continuous unit only in the vicinity of Nepco Lake and the area south of the lake, where it occurs as a coarse calcareous silt layer 0.3 to 1 m thick, typically at a depth of 9 to 12 m (Brownell, 1986).

Hydraulic conductivity

Table 1 summarizes the results of aquifer tests in the stream and lake sediment at several locations in the study area and shows it to have consistently high hydraulic conductivity, more than 10^{-4} m/s. Estimates of hydraulic conductivity in table 1 are based on several different methods, including pumping tests, specific-capacity tests, piezometer slug tests, and laboratory permeameter tests. The appendix summarizes the results of a series of piezometer slug tests in the Buena Vista basin conducted especially for this study. The *in situ* tests (pumping, specific-capacity, and slug tests) probably estimate field conditions more accurately than do the laboratory permeameter tests. In particular, the pumping and specific-capacity test results apply to larger volumes of aquifer material than the slug tests, which are essentially point measurements (Bradbury and Muldoon, 1990).

Groundwater flow

Groundwater in the Buena Vista basin moves generally from east to west, from higher to lower hydraulic head along paths perpendicular

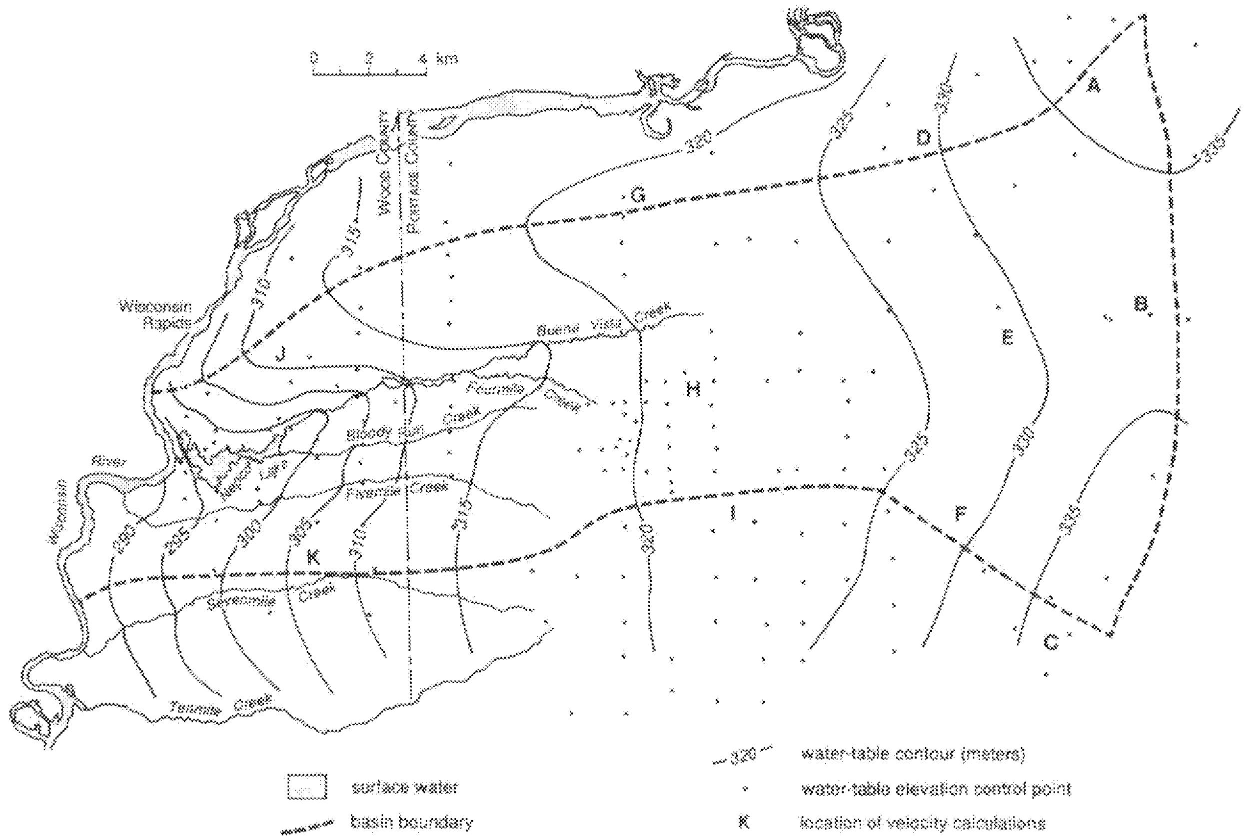


Figure 5. *Water-table map of the Buena Vista basin based on data collected in August 1984.*

to the water-table contours. Although aquifer heterogeneities might alter this pattern in places, the known range of hydraulic conductivity (table 1) is probably not great enough to alter the regional groundwater flow pattern markedly. The water-table map shown in figure 5 was constructed from water-level measurements made during the period August 20 to 22, 1984. Through an analysis of water-table fluctuations in the sand plain, Blanchard and Bradbury (1987) suggested that the August 1984 map is characteristic of overall yearly water-table levels.

Pattern of groundwater flow

The water-table configuration shown in figure 5 indicates that regional groundwater flow (which originates at the regional groundwater divide and discharges to the Wisconsin River) probably does not occur in the Buena Vista groundwater basin. Instead, the equipotential lines along Fourmile Creek indicate that most groundwater flow in the basin discharges into the creek long before it reaches the Wisconsin River.

The convergent flow pattern created by Fourmile Creek makes it impossible to define a straight-line cross section parallel to the groundwater flow direction from the regional groundwater divide to the regional groundwater discharge boundary. The Buena Vista groundwater basin differs from the simplified conceptual models presented in figure 4 because the groundwater flow pattern is complex in the horizontal as well as the vertical plane. As in

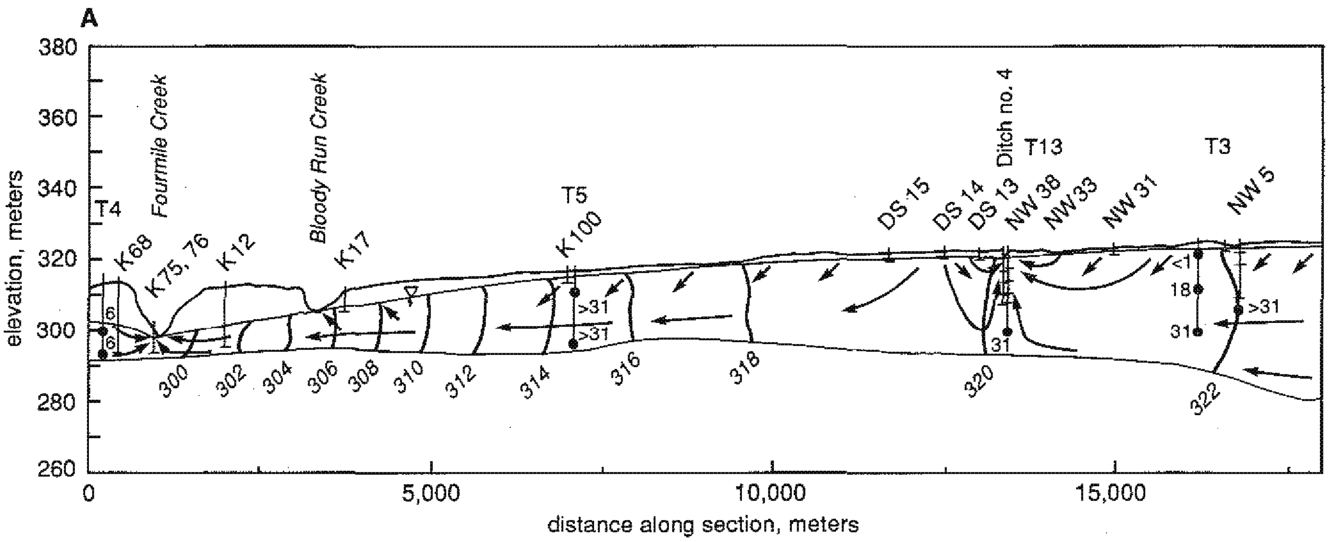


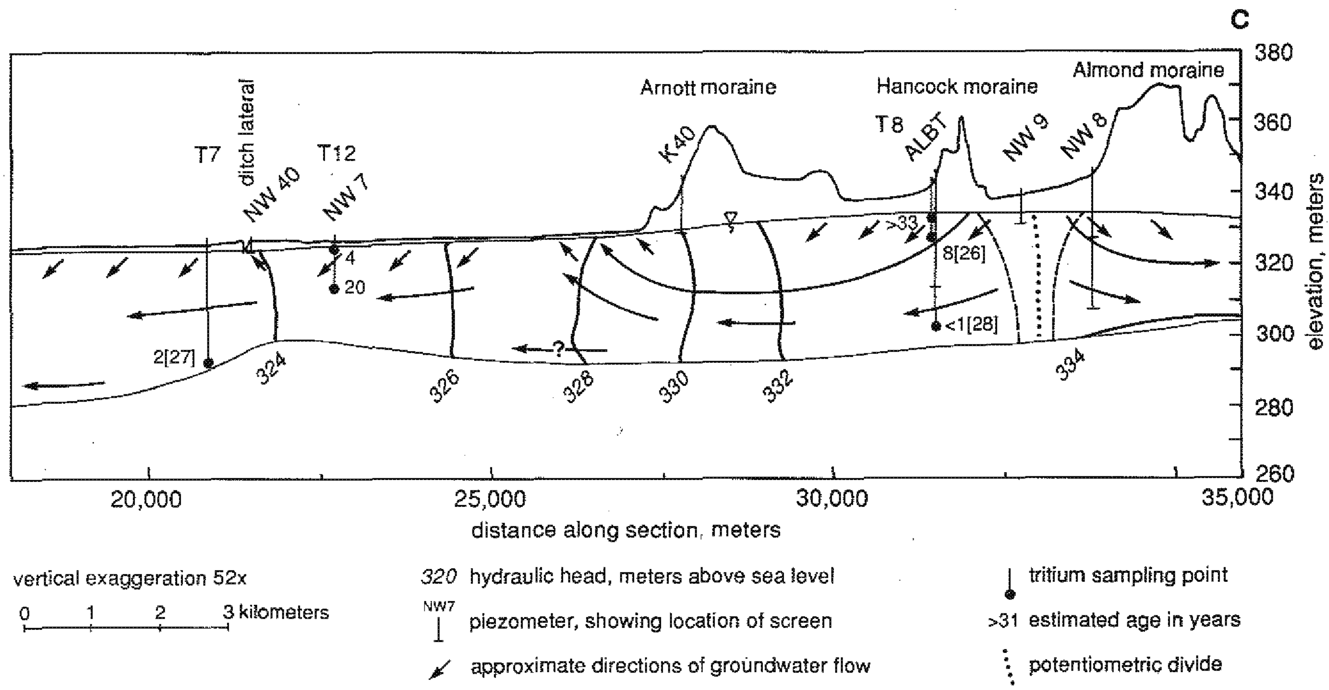
Figure 6. *Cross section through the Buena Vista basin along line A–C (see fig. 2), showing general direction of groundwater movement. Estimated minimum groundwater ages are shown for selected sites. Ages in brackets are alternative interpretations based on flow-system geometry and tritium input record.*

most natural groundwater flow systems, flow in the basin is three-dimensional and not easily displayed in two dimensions.

It is important to consider the pattern of vertical groundwater flow to gain a more complete understanding of the groundwater flow system. Figure 6 shows the groundwater flow pattern along the curvilinear vertical cross section A–C, the location of which is shown in figure 2. The cross section is approximately parallel to the direction of groundwater flow. The flow lines shown in figure 6, although schematic, are based on hydraulic gradients measured by piezometers. The water-table configuration shown was taken from the April 1984 water-table map of Faustini (1985); the cross-sectional flow pattern is representative of the pattern during and after spring recharge, when local flow systems are well developed. The cross section shows that groundwater entering the aquifer between the Arnott and Hancock moraines can discharge in wetlands just west of the moraines, and that drainage ditch 4, Bloody Run Creek, and Fourmile Creek are also important discharge points. The flow pattern for August 1984 (not shown) is similar, except that ditch 4 receives less discharge and substantial underflow occurs.

Tritium content and relative age of groundwater

The tritium content of groundwater provides a measure of the relative age of groundwater in the Buena Vista basin. Tritium (^3H) is a radioactive isotope of hydrogen that entered the earth's atmosphere in elevated amounts as a consequence of the atmospheric nuclear weapons testing that began about 1953. Since that time, precipitation in most parts of the world has contained elevated levels of tritium. Atmospheric tritium levels reached a maximum about 1963 and steadily declined following the cessation of



atmospheric testing in the mid-1960s. Tritium in precipitation at Madison, Wisconsin, was about 8 to 10 tritium units (1 tritium unit, or TU, is one tritium atom per 10^{18} hydrogen atoms) prior to 1953 (Thatcher, 1962), reached a peak of more than 4,500 TU during 1963, and declined to 20 to 30 TU by 1986. Bradbury (1991) presented the tritium input history for central Wisconsin and discussed a method for estimating groundwater age using the tritium content of water samples.

During 1984 and 1986, 27 water samples were collected from piezometers at 15 sites fairly evenly distributed throughout the Buena Vista basin (fig. 2). In general, the samples were collected from several piezometers at each site to assess the variation of tritium with depth below the water table. Sample depths, controlled by the positions of the piezometer screens, ranged from just below to 32.7 m below the water table. The samples were tested for tritium content at the University of Waterloo (Ontario, Canada) Isotope Laboratory by direct liquid scintillation counting, with a detection limit of 2 to 6 TU. Tritium content of the samples ranged from not detectable to 157 TU (table 2). On the basis of the tritium content and the historic record of tritium in recharge (fig. 7), the estimated minimum age, or residence time, of groundwater in the Buena Vista basin ranged from less than one year to more than 33 years at the time of sampling (table 2). Although groundwater can be older than the estimated minimum age, it cannot be younger. The mean minimum age, based on the 27 tritium samples, was about 13 years at the time of sampling.

Samples at five sites (T3, T5, T8, T14, and T15) contained no detectable tritium, and one sample from site T13 contained only 2 TU. Groundwater at these sites apparently recharged prior to the advent of nuclear weapons testing and was therefore probably more than 31 years old at the time of sampling. The maxi-

Table 2. *Tritium content of groundwater in the Buena Vista basin. Tritium sites are indicated on figure 1; recharge and discharge classifications are from Faustini (1985) and Stoertz and Bradbury (1989).*

Tritium site	Piezometer	Area class[1]	Sample date	Depth below water table (m)	Tritium (TU)	Minimum age at sampling (yr)	Interpreted age (yr)
T1	NW10A	R	06/10/86	3	41	6	6
T1	NW10B	R	06/05/84	9	43	6	6
T2	NW11F	T	06/05/84	33	106	17	17
T3	NW26A	R	06/10/86	1	18	<1	<1
T3	NW26C	R	10/22/84	9	157	18	18
T3	NW26D	R	06/05/84	20	ND[2]	31	31
T4	K61	R	06/10/86	2	39	6	6
T4	K60	R	06/05/84	11	62	6	6
T5	PT776	D	10/22/84	7	ND	31	31
T5	PT777	D	06/05/84	19	ND	31	31
T6	NURS3	T	06/05/84	7	68	13	13
T6	NURS4	T	06/05/84	9	40	3	3
T7	CHIC4	T	06/06/84	33	29	2	27
T8	NW1A	T	06/10/86	1	ND	33	33
T8	NW1B	T	06/10/86	6	48	8	26
T8	ALBT4	T	06/05/84	31	19	<1	28
T9	NW48A	D	06/10/86	0	38	4	4
T9	NW48C	D	06/10/86	6	34	3	3
T9	NW48E	D	10/22/84	12	33	<1	<1
T10	NW56	R	06/10/86	4	21	<1	<1
T11	NW58	R	06/10/86	2	48	8	8
T12	NW7A	R	06/10/86	1	38	4	4
T12	NW7B	R	06/10/86	12	137	20	20
T13	NW33F	D	10/22/84	21	2	31	31
T14	NW2A	R	06/10/86	2	15	<1	<1
T14	NW2B	R	06/10/86	12	ND	33	33
T15	NW4D	D	10/22/84	15	ND	31	31

[1] R: recharge; T: transitional; D: discharge
[2] not detected

mum measured depth of such "pre-bomb" water was 21 m below the water table at site T13, and the minimum depth of pre-bomb water was 1 m below the water table at site T8.

The estimated minimum ages are consistent with the cross-sectional flow patterns shown in figure 6. In general, the oldest groundwater occurs near the end of long flow paths. The anomalously young ages at sites T7 (piezometer CHIC4) and T8 (piezometers NW1B and ALBT4) appear to have resulted from the depth of the piezometers and their positions in the groundwater flow system. It seems likely that groundwater at these sites recharged prior to the 1963 atmospheric tritium peak (Bradbury, 1991). If so, actual ages would be much greater than the minimum ages estimated above. Using this interpretation, groundwater at site T7 entered the aquifer about 1957 and would thus have been about 27 years old at the time of sampling; groundwater ages at site T8 (piezometers NW1B and ALBT4) were 26 and 28 years, respectively. These interpreted ages, shown in brackets in figure 6, fit the groundwater flow interpretations.

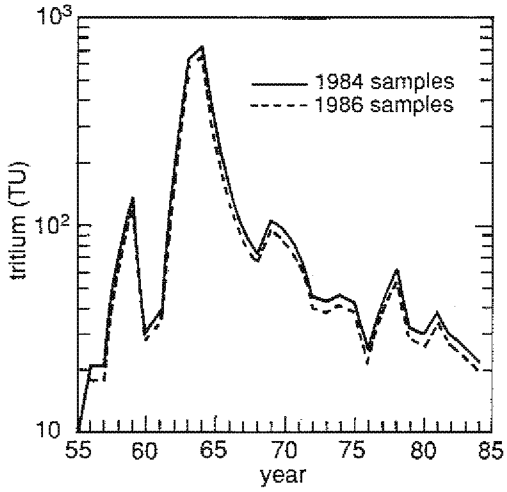


Figure 7. *Weighted tritium input for central Wisconsin, corrected for radioactive decay to 1984 and 1986.*

Occurrence of pre-bomb water in the shallow piezometer at site T8 is interesting because tritium is present in deeper piezometers at 6 and 31 m below the water table. Site T8 lies on the Hancock moraine, where more than 24 m of unsaturated till covers the aquifer. Recharge through the moraine is apparently much slower than is recharge to and groundwater flow from the area between the Hancock and Almond moraines. The younger ages at depth apparently reflect the influence of lateral inflow at site T8 and not the vertical recharge pattern seen at the other sites.

Groundwater velocity

The rate of groundwater movement (average linear velocity) is related to the total groundwater flux through the system, and hence to the amount of groundwater available for use. In addition, the groundwater velocity distribution governs the rate at which contaminants in the groundwater can be transported.

Groundwater movement in the Buena Vista basin is three dimensional, meaning that the water moves horizontally and vertically at the same time. Because of the difficulties associated with measuring and portraying groundwater movement in three dimensions, in this report we discuss groundwater movement in terms of either the horizontal or vertical component of flow. Even though we discuss the two flow components separately, most groundwater actually moves along curving flow paths that have vertical and horizontal components.

The horizontal component of average linear groundwater velocity can be calculated using Darcy's law as

$$\overline{v}_h = -(K_h/n)(dh/dx), \qquad (1)$$

where $\overline{v}_h$ is average linear horizontal velocity,

K_h is the horizontal hydraulic conductivity of the aquifer,

n is the effective porosity, and

dh/dx represents the horizontal hydraulic gradient, or change in hydraulic head (h) over some horizontal distance (x).

Similarly, the vertical component of average linear groundwater velocity is

$$\overline{v}_z = -(K_v/n)(dh/dz), \qquad (2)$$

where $\overline{v}_z$ is average linear vertical velocity,

K_v is the vertical hydraulic conductivity of the aquifer, and

dh/dz represents the vertical hydraulic gradient, or change in hydraulic head (h) over some vertical distance (z).

The negative sign in front of the (K_v/n) term in Darcy's law shows that the average velocity is in the downgradient direction. This requirement can cause confusion when discussing the field measurement of vertical hydraulic gradients because a given gradient can be either negative or positive depending on the choice of a datum. In this report, when discussing vertical hydraulic gradients, we use the words "upward" and "downward" to refer to the gradient and to the direction of the vertical component of groundwater flow relative to the land surface.

Horizontal component of groundwater movement

Table 3 summarizes calculated horizontal components of groundwater velocity in various parts of the regional flow system. The horizontal hydraulic gradients are assumed to be equal in magnitude to the water-table slope, determined from the water-table map at locations A through K in figure 5. These velocity estimates are for the general area of the basin around each location rather than for the exact location of the symbol of figure 5. The values used for hydraulic conductivity are based on specific aquifer test results reported by Faustini (1985). For each calculated velocity, we used the hydraulic conductivity value from the nearest test location, or one judged most comparable on the basis of geologic considerations. An effective porosity of 32 percent (Holt, 1965) is assumed in all the velocity calculations. This is somewhat less than the average porosity of 39.5 percent measured by Stoertz (1985) at a site near Wisconsin Rapids, but it is probably more appropriate for an overall basin average.

The calculated horizontal component of groundwater velocity is typically about 0.3 m/day in the Buena Vista basin and ranges from about 0.15 m/day in the central marshy area of the basin to around 0.6 m/day in the coarse stream sediment west of the Arnott moraine near Arnott. In general, the groundwater velocity is highest where topographic relief is high (from the moraines to the Buena Vista marsh and near major discharge areas such as the lower Buena Vista Creek and the Wisconsin River) and lowest where relief is low (in the central marshy area of the basin). In places, horizontal groundwater velocities considerably in excess of 0.6 m/day probably occur in the basin, particularly near discharge areas such as major drainage ditches and the Wisconsin River.

Table 3. *Representative horizontal components of groundwater velocity in the Buena Vista groundwater basin, based on hydraulic calculations. See figure 5 for locations of calculation points.*

Position in basin			Horizontal hydraulic gradient[1]	Horizontal hydraulic conductivity[2] (m/s)	Average horizontal linear velocity[3] (m/d)
Groundwater divide	North	A[4]	0.0012	8.1×10^{-4}	0.3
	Central	B	0.00031	1.8×10^{-3}	0.2
	South	C	0.0052	9.7×10^{-4}	0.2
Slope below moraines	North	D	0.0013	1.8×10^{-3}	0.6
	Central	E	0.0014	9.7×10^{-4}	0.4
	South	F	0.0018	8.1×10^{-4}	0.4
Central basin	North	G	0.00046	1.1×10^{-3}	0.2
	Central	H	0.00049	1.1×10^{-3}	0.2
	South	I	0.00050	1.1×10^{-3}	0.2
Lower basin	North	J	0.0016	7.4×10^{-4}	0.3
	South	K	0.0020	7.4×10^{-4}	0.4
Basin average					0.3

[1] estimated from the August 1984 water-table map
[2] compiled by Faustini (1985, table 4.1)
[3] based on a porosity of n=0.32
[4] symbol on figure 5 showing location to which calculated velocity applies

Horizontal groundwater velocities based on the tritium results are consistent with velocities based on hydraulic calculations. Six of the velocity calculation sites in table 3 are near tritium sampling sites, where groundwater flow was expected to be primarily horizontal. Estimated average linear groundwater velocities based on tritium data were calculated at these six sites by dividing the length of the horizontal groundwater flow path (the distance along a flow line from each tritium site to the upgradient groundwater divide) by the estimated groundwater age at the deepest piezometer at that site.

Estimated groundwater velocities based on tritium range from <0.2 to 1.7 m/day (table 4), with velocities at three sites being less than or equal to the computed values because the associated piezometers contained pre-bomb water. Agreement between the tritium and hydraulic velocity estimates was excellent at two sites (T8 and T14) and within a factor of two or three at the four other sites. Velocity estimates based on Darcy's law could be subject to errors of up to 30 percent in the hydraulic conductivity term and probably 20 percent in the porosity term, but the relatively good agreement between the two independent methods suggests that these estimates are of the correct order of magnitude.

Estimates of horizontal groundwater velocity were generally not possible at other tritium sampling sites because of uncertainty about the lengths of groundwater flow paths, the presence of significant vertical flow, and the possibility of groundwater mixing along longer flow paths.

The calculated velocities in tables 3 and 4 are representative of horizontal groundwater flow under natural conditions. Groundwater velocities in the vicinity of high-capacity wells are increased in magnitude and altered in direction during periods of pumping. These effects could markedly alter the movement of contaminants in groundwater as predicted by natural flow conditions. The effects of wells on groundwater flow are transient and small in areal extent, and they must be taken into account on a case-by-case basis when predicting the movement of contaminants in groundwater.

Vertical component of groundwater movement

Groundwater in the Buena Vista basin moves vertically as well as horizontally from areas of higher total hydraulic head to areas of lower total hydraulic head. Measurements of total hydraulic head at vertically spaced points within the aquifer were obtained from the piezometer nests installed for this study (fig. 2). Table 5 expresses these hydraulic head differentials as vertical hydraulic gradients, where each gradient is calculated as the head differential be-

Table 4. *Average linear horizontal velocities of groundwater at six sites in the Buena Vista basin, calculated from tritium data and using Darcy's law (table 3).*

Tritium site	Nearest velocity site	Deepest piezometer	Interpreted age based on tritium (yr)	Upgradient flow path length (m)	Estimated average linear velocity (m/day)	
					Tritium (TU)	Darcy's law
T1	A	NW10B	6	1,370	0.6	0.3
T2	D	NW11F	17	10,500	1.7	0.6
T3	I	NW26D	>31	14,600	<1.3	0.2
T8	B	ALBT4	28	1,600	0.2	0.2
T14	C	NW2B	>33	2,100	<0.2	0.2
T15	H	NW4D	>31	16,100	<1.4	0.2

tween the deepest and shallowest piezometers in each nest divided by the vertical distance between the piezometer screens. Table 5 shows average vertical gradients measured over the period of study at each piezometer.

Vertical hydraulic gradients in the Buena Vista basin are generally about the same magnitude as the horizontal gradients. The vertical change in total hydraulic head at a given location is rarely more than a few centimeters over the thickness of the aquifer. Vertical gradients at the 20 piezometer nests analyzed in table 5 range from 0.0001 (flow upward) to -0.05 (flow downward). The average gradient was -0.002; the smallest measurable gradient was 0.0001 at nest NW33. At two nests, NW11 and NW25, there was no measurable vertical gradient.

The lack of large vertical hydraulic gradients in the Buena Vista basin means that water levels in wells and piezometers of varying depths can be used to construct maps of the regional configuration of the water table in the central sand plain and similar areas having sandy, unconfined aquifers (Blanchard and Bradbury, 1987). Such maps can be used to predict the general direction of regional horizontal

Table 5. *Summary of vertical hydraulic gradients and vertical components of velocity calculated at piezometer nests in the Buena Vista basin. Gradients were calculated from the average hydraulic heads in each pair of piezometers. Probable maximum and minimum values of vertical hydraulic conductivity were based on the anisotropy ranges of Weeks (1964), using horizontal hydraulic conductivity values taken from the appendix (this report) and Faustini (1985); maximum and minimum values of vertical average linear velocity were calculated using an effective porosity of 0.32. Site locations are shown in figure 2.*

Piezometers	Vertical hydraulic gradient[1]	Vertical hydraulic conductivity minimum (m/s x 10^{-4})	Vertical hydraulic conductivity maximum (m/s x 10^{-4})	Vertical average linear velocity minimum (m/d)	Vertical average linear velocity maximum (m/d)	Direction of flow
ALBT1, 4	0.0005	0.06	0.6	0.0008	0.008	up
CHIC1, 4	-0.001	0.05	0.5	0.001	0.01	down
NURS1, 2	0.001	0.1	1.0	0.003	0.03	up
NURS3, 4	-0.05	0.001	0.01	0.002	0.02	down
NW01A, 1B	-0.009	0.2	2.0	0.05	0.5	down
NW02A, 2B	-0.002	0.5	5.0	0.03	0.3	down
NW04A, 4C	0.008	0.2	2.0	0.05	0.5	up
NW07A, 7B	-0.008	0.5	5.0	0.1	1.0	down
NW08A, 8B	-0.001	0.2	2.0	0.006	0.06	down
NW10A, 10B	-0.0002	0.4	4.0	0.002	0.02	down
NW11A, 11F	0	0.9	9.0	0.000	0.0	—
NW19A, 19B	0.005	0.3	3.0	0.04	0.4	up
NW25A, 25E	0	0.9	9.0	0.000	0.0	—
NW26A, 26D	0.001	0.1	1.0	0.003	0.03	up
NW27A, 27B	0.003	0.1	1.0	0.009	0.09	up
NW29A, 29C	-0.0002	0.4	4.0	0.002	0.02	down
NW32A, 32D	-0.0006	0.4	4.0	0.005	0.05	down
NW33A, 33F	0.0001	0.3	3.0	0.0008	0.008	up
NW38A, 38E	0.001	0.3	3.0	0.009	0.09	up
NW48A, 48E	0.0007	0.2	2.0	0.005	0.05	up

[1] measured in pairs of nested piezometers

groundwater movement. Combining the vertical hydraulic gradients measured at piezometer nests with estimates of vertical hydraulic conductivity gives estimated rates of vertical groundwater flow in the study area.

There have been few actual measurements of vertical hydraulic conductivity in the central sand plain; pumping tests or piezometer slug tests generally give values of horizontal hydraulic conductivity. Weeks (1969) conducted several detailed aquifer pumping tests in and around the Buena Vista basin and concluded that the ratio of vertical to horizontal hydraulic conductivity in the aquifer ranges from about 1:2 to 1:20. Using this range of anisotropy ratios, and assuming an effective porosity of 32 percent (Holt, 1965), minimum and maximum vertical average linear groundwater flow velocities can be estimated using Darcy's law (equation 2 and table 5).

Maximum estimated vertical groundwater flow velocities calculated for various sites range from about 1 m/day downward to 0.5 m/day upward (table 5). As with horizontal velocity components, the estimated vertical velocities represent groundwater movement under natural conditions. Vertical flow velocities can be much greater near pumping wells. The velocities in table 5 are rough estimates, but show the order of magnitude, range, and direction of vertical groundwater movement in the study area. In general, vertical flow velocities are smaller than horizontal flow velocities. More accurate evaluations of vertical groundwater movement at particular sites should be based on detailed measurements of vertical gradients, vertical hydraulic conductivity, and porosity.

Hydrogeologic boundaries

The central sand plain of Wisconsin is a large region of relatively uniform geologic and hydrogeologic characteristics. For groundwater research, planning, or management, it is convenient to work with smaller areas, according to the degree of detail required by the project. We define hydrogeologic boundaries as real or imaginary vertical planes across which no significant groundwater flow occurs. Boundaries to lateral groundwater flow in the central sand plain are controlled primarily by topography and the distribution of streams, including perennially flowing drainage ditches, rather than by geology.

Boundary types

We have determined four types of hydrogeologic boundaries in the study area.

- *Major or regional groundwater divide*—a groundwater divide associated with a major topographic divide between major rivers or streams. For example, the eastern boundary of the Buena Vista groundwater basin (fig. 2) follows the Hancock and Almond moraines, which form the divide between the Wisconsin River basin to the west and the Wolf River basin to the east.
- *Local groundwater divide*—a groundwater divide between local surface-water features. The northern boundary and the western part of the southern boundary of the Buena Vista groundwater basin are local divides.
- *Flow-line boundary*—a boundary drawn parallel to the direction of groundwater flow where equipotential lines are at their maximum downgradient flexure and no well defined groundwater divide exists. The eastern part of the southern boundary of the Buena Vista groundwater basin is a flow-line boundary.
- *Groundwater discharge boundary*—a relatively large surface-water feature that receives continuous groundwater discharge and is effectively fully penetrating (that is, no groundwater flow crosses it). The Wisconsin River and Fourmile Creek below the junction with Buena Vista Creek are examples of this type of boundary.

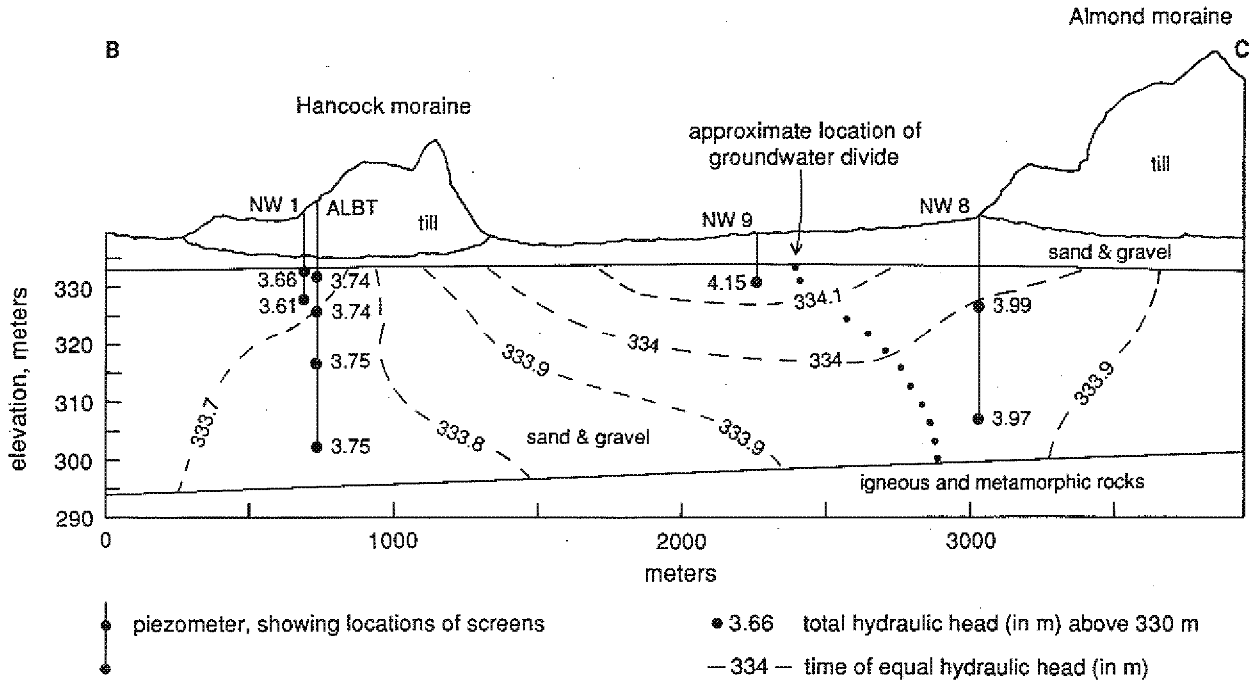


Figure 8. *Cross section showing groundwater flow patterns and estimated groundwater ages along cross section B–C (see fig. 2), located along the eastern groundwater divide.*

Small streams that receive continuous or nearly continuous groundwater discharge may be effective discharge boundaries, if they are fully penetrating (Zheng and others, 1988a, 1988b). The numbered drainage ditches, Fivemile Creek, and Buena Vista and Fourmile Creeks above their junctions may be discharge boundaries.

Regional groundwater divide

Regional groundwater divides are well defined features in most areas and generally can be delineated with reasonable accuracy from regional water-table maps. Such divides are fully penetrating boundaries to groundwater flow. They are associated with major topographic divides but not necessarily coincident with them.

Part of the regional groundwater divide between the Wisconsin and the Wolf and Waupaca River basins forms the eastern boundary of the Buena Vista groundwater basin. This boundary lies subparallel to and 0.5 to 5 km west of the topographic divide (fig. 2), the distance increasing southward. Piezometers were installed at three sites along a cross section through the groundwater divide (fig. 8) to define the location of the divide more precisely and to check whether near-vertical downward groundwater flow occurs there.

The hydraulic head data indicate the presence of a groundwater divide between the Hancock and Almond moraines. Vertical gradients at sites NW1 and NW8 (table 5) indicate downward flow as expected, although the gradients are an order of magnitude stronger at site NW1 than at NW8. A nest of four piezometers installed to a depth of 41 m at the ALBT site (only 61 m from NW1; fig. 2), however, indicated generally negligible vertical gradients. Apparently, recharge in the sandy, level area between the Hancock and Almond moraines is more rapid than recharge through the moraines. Discharge into the head of a perennial stream that originates in a water gap about 0.4 km southwest of the ALBT site could produce convergent groundwater flow. This might account for the conflicting gradients along the west side of the Hancock moraine. Another possible explanation for the conflicting hydraulic gradients is preferential flow of groundwater through gravel bars and other heterogeneities associated with channel deposits.

Local groundwater divides

Local groundwater divides form most of the northern and southern boundaries of the Buena Vista groundwater basin. These divides are well developed in the western part of the basin, but they become less distinct farther east. Local groundwater divides also occur between the drainage ditches in the central part of the basin, but they are evident only on a detailed water-table map.

Some care must be exercised when treating local groundwater divides as "no-flow" boundaries (no component of flow perpendicular to the trend of the divide) because underflow can occur at depth, particularly in areas where local divides are close to a regional groundwater divide.

Flow-line boundaries

A flow-line boundary is used for convenience where no well defined groundwater divide exists. The boundary must be parallel to groundwater flow, but its exact placement is arbitrary. This type of boundary is commonly used in computer modeling studies, where it is treated as a no-flow boundary in the same way as a groundwater divide. Flow-line boundaries are sensitive to the slope of the water table and can migrate in response to seasonal water-level changes.

Groundwater discharge boundaries

Unlike groundwater divides, which do not necessarily coincide with topographic divides, major groundwater discharge boundaries generally do coincide with topographic lows, such as major streams, and can often be delineated directly on the basis of topographic maps. Major rivers, such as the Wisconsin River, can be mapped with confidence as groundwater discharge boundaries. Large tributaries, such as the Plover River, can also be no-flow boundaries, but should not be assumed to be fully penetrating; a nearby river at a lower elevation might induce underflow beneath the tributary.

Major groundwater discharge boundaries are not necessarily areas of regional groundwater discharge. For example, most or all of the groundwater discharging directly into the Wisconsin River from the Buena Vista groundwater basin probably originates within 1 to 4 km of the river because groundwater derived from higher in the basin is intercepted by Buena Vista and Fourmile Creeks.

Hydraulic head and streamflow measurements (Faustini, 1985), along with computer studies (Zheng and others, 1988a), show that the numerous drainage ditches in the central sand plain can be significant boundaries to groundwater flow, but the effective depth of these boundaries can vary seasonally. Part of one ditch was found to be a discharge area for groundwater flow through the entire aquifer thickness from late spring through midsummer of 1984, but partial damming of water in the ditch due to channel clogging by vegetation caused a reversal of seepage through the stream bed in late summer. Perennial flow, including open water throughout the winter, indicates that the ditches receive groundwater discharge all year. If these ditches receive groundwater from the entire aquifer thickness over most of a typical year, they constitute significant boundaries to lateral groundwater movement.

It would be convenient to use the many streams and drainage ditches in the central sand plain to divide the region into smaller units for groundwater resource planning and management. However, because all these streams may

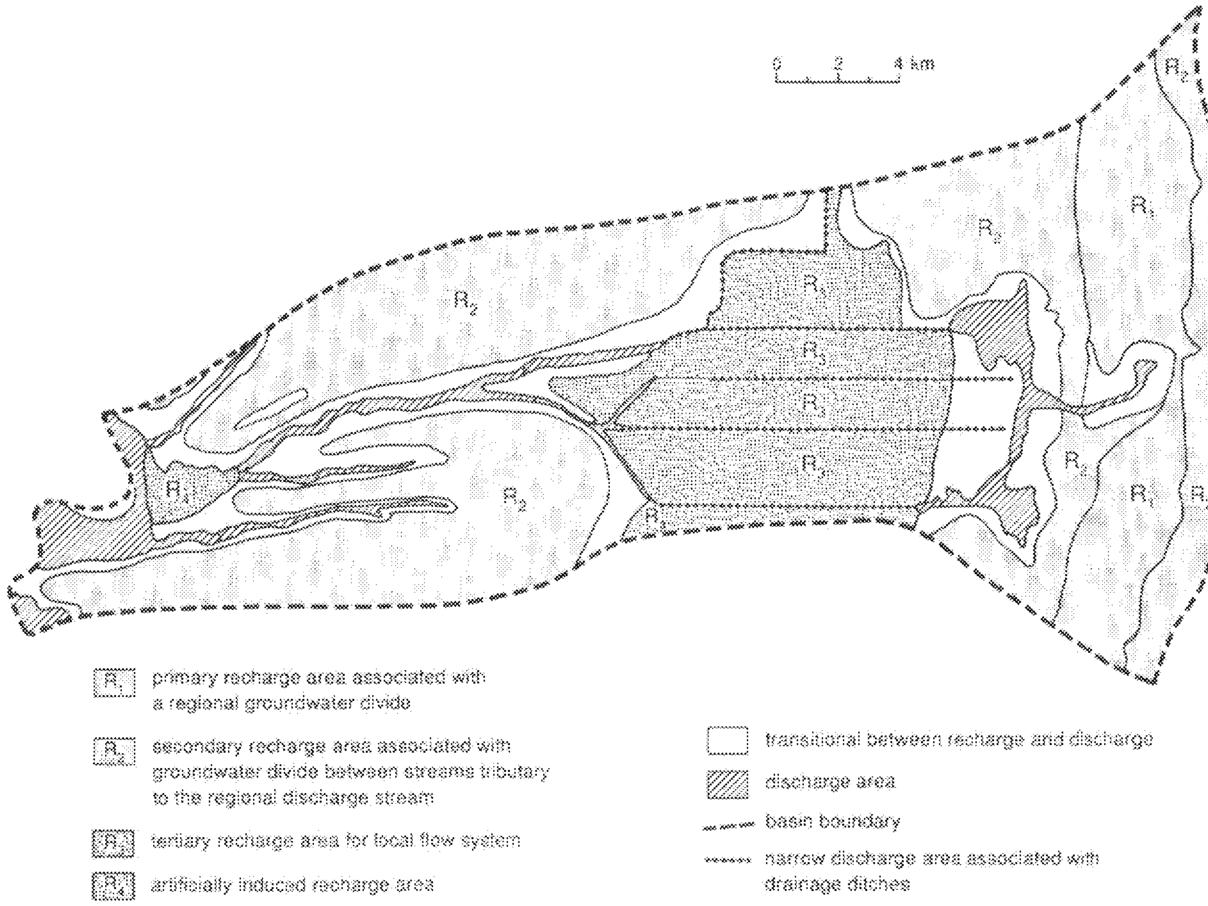


Figure 9. *Field map of groundwater recharge and discharge areas in the Buena Vista basin (modified from Faustini, 1985).*

not be hydraulically fully penetrating, the relationship of each stream to the groundwater flow system must be checked by field measurements before that stream can be accepted with confidence as a groundwater flow boundary (Faustini, 1985). Zheng and others (1988a, 1988b) developed analytical and numerical modeling techniques for determining whether streams or drainage ditches act as fully penetrating boundaries.

Stratigraphic hydrogeologic boundaries

The boundaries to lateral groundwater flow discussed above have a nearly vertical orientation and appear as linear features when mapped. Areally extensive, nearly horizontal hydrogeologic boundaries also exist, but they are usually stratigraphically controlled boundaries. One such boundary is the contact between the unlithified sediment and the underlying rock, assumed in this study to be relatively impermeable. Another stratigraphic boundary, located within the unlithified sediments, is the silty New Rome Member of the Big Flats Formation (Attig and others, 1988), found in most of the central sand plain south and west of the study area (Brownell, 1986). The hydrogeologic significance of this unit, which is up to 9 m thick in southern Adams County, is demonstrated by artesian flow from test holes in Juneau County where the unit was penetrated (J. Brownell, 1985, verbal communication). This unit acts as a regional aquitard in the areas where it occurs in the subsurface. Other discontinuous silty layers occur either above or below the water table in the Buena Vista basin. Stoertz (1985) described one such layer at a site near Wisconsin Rapids.

Delineation of recharge and discharge areas

The areal distribution of groundwater recharge and discharge areas has important implications for groundwater planning and management and is fundamental to an understanding of groundwater flow systems. Groundwater flow paths originate in recharge areas and terminate in discharge areas; the distribution of these areas provides information about groundwater flow patterns and the length of groundwater flow paths.

Map of recharge and discharge areas

Figure 9 (modified from Faustini, 1985) shows the recharge and discharge areas in the Buena Vista groundwater basin and vicinity. Using the methods of Meyboom (1966) and Toth (1966), we divided the area into five recharge or discharge units on the basis of field observations. The specific field indicators that we used include geomorphic features, the configuration of the water table (determined from piezometric patterns and topography), vertical hydraulic gradients, depth to the water table, fluctuations of the water table, and streams and lakes. Table 6 summarizes the map units. The map is interpretive, and all parameters were not measured at all points. Construction of the map relied most heavily upon topography, water-table configuration, and surface hydrologic features such as marshes, streams, and drainage ditches. We used the other information primarily to confirm and refine the resulting pattern of recharge and discharge areas.

Four recharge units are distinguished in figure 9. The *primary* or *regional recharge area* (R_1) is associated with the regional groundwater divide. This area has a persistent downward component of groundwater flow, and there is little or no lateral groundwater flow into this area. *Secondary recharge areas* (R_2) are associated with intermediate or local groundwater divides, or with moraines that impede recharge. They are otherwise similar to the regional recharge area, except that underflow can occur beneath them. Groundwater at depth beneath a secondary recharge area may originate from the primary recharge area. *Tertiary recharge areas* (R_3) occur between the drainage ditches in the Buena Vista marsh area. The downward component of groundwater flow may not be persistent in these areas, and underflow may occur. *Artificially induced recharge areas* (R_4) occur where groundwater has been impounded behind a dam, such as near Nepco Lake.

Discharge areas are lumped together in figure 9. Primary discharge areas are zones of persistent upward groundwater flow and continuous groundwater discharge, which are associated with the Wisconsin River and the lower parts of important tributaries. Little or no underflow occurs beneath these areas. Local discharge areas occur near the middle of the basin. Underflow beneath secondary discharge areas is possible but probably does not occur in the Buena Vista groundwater basin because of the development of deep intermediate and local flow systems (Zheng and others, 1988a). Local, narrow discharge areas also occur at the streams and drainage ditches in the central part of the basin and may or may not receive continuous groundwater discharge. Artificially induced discharge areas are caused by heavy pumping of wells on a continuous or nearly continuous basis. Such artificial discharge is not associated with upward groundwater flow because the discharge occurs below the water table.

Figure 9 also shows a transitional zone between recharge and discharge areas. This unit was included on the map because it is generally not possible to define the boundary between recharge and discharge areas precisely, and because the zone boundaries can shift seasonally.

Table 6. *General characteristics of selected indicators of groundwater recharge used to construct figure 9. Numerical ranges are approximate.*

Map unit	Unit name	Topography	Water-table slope (m/km)	Water-table depth (m)	Water-table fluctuation[1] (m)	Vertical hydraulic gradients
R_1	Primary recharge area	Steep moraines and outwash fans	0.1–1	8–30	0.3–0.6	Always downward
R_2	Secondary recharge area	Minor topographic divides	0.5–3	2–8	0.3–1.5	Usually downward
R_3	Tertiary recharge area	Flat	0.1–0.5	1–2	0.6–1	Net downward
R_4	Artificially induced recharge area	Stream valleys	?[2] (steep)	——[3]	——	Always downward; may be very strong

[1] based on water-level measurements reported by Karnauskas (1977) for the period July 1976 to April 1977
[2] insufficient data
[3] non-characteristic parameter

The tritium data (table 2) tend to support the groundwater recharge and discharge interpretations summarized in figure 9. In general, groundwater age should increase down a groundwater flow path; consequently, groundwater in discharge areas should be older than groundwater in recharge areas. Table 7 groups the tritium data into samples from mapped recharge, transitional, and discharge areas. Where more than one tritium analysis was obtained from a given site, the arithmetic mean of all values from that site was used in constructing table 7. Although the range of tritium values and estimated ages within any particular area is large, as shown by the large standard deviations, the median interpreted groundwater ages increase from 8 years old in recharge areas to 22 years old in transitional areas to 31 years old in discharge areas.

However, common parametric statistics based on the data in table 7 may not be meaningful because the sample sizes are small and because the data may not be normally distributed. However, the nonparametric Mann-Whitney method (Ryan and others, 1985) provides a valid test of the equality of medians for such small populations. According to this test, the median age of groundwater at the seven sites in mapped recharge areas (8 years old) is significantly less than the median minimum age of groundwater at the four sites in transitional areas (22 years old) at a confidence level of 93 percent and is significantly less than the median minimum age at the four sites in discharge areas (31 years old) at a confidence level of 85 percent. Groundwater ages at transitional and discharge areas were not significantly different at greater than the 69 percent confidence level. This low level of significance is not surprising because groundwater flow paths in the Buena Vista basin have varying lengths. Thus, water in the discharge area of a short flow system can be the same age as water in the transitional area of a longer flow system. Groundwater at sites in mapped recharge areas was younger (8 years old) than groundwater in the combined group

Table 7. *Tritium content and estimated minimum groundwater ages for recharge, discharge, and transitional areas in the Buena Vista basin.*

Area	Number of sites	Median estimated age (yr)	Standard deviation
Recharge	7	8	6
Transitional	4	22	10
Discharge	4	31	14
Transitional plus discharge	8	28	11

of transitional and discharge areas (28 years old) at a confidence level of 96 percent.

Modeled recharge and discharge areas

The recharge and discharge areas determined by field methods were confirmed and in some areas refined by a computer-aided mapping technique using a map of the water table, Darcy's law, and the law of conservation of mass.

This mapping technique (Stoertz, 1985; Stoertz and Bradbury, 1989) is a type of inverse groundwater modeling based on a water balance for each node in a finite-difference grid. All model nodes are treated as constant-head nodes, and the head at each node is interpolated from the water-table map. On the basis of Darcy's law and the law of conservation of mass, the model calculates a recharge or discharge flux for each node. These fluxes are then used to construct a map. This technique was facilitated by using a modified version of the U.S. Geological Survey three-dimensional modular finite-difference flow computer code (McDonald and Harbaugh, 1988; Stoertz and Bradbury, 1989). The basin was modeled using a 16 by 32 node finite-difference grid (fig. 10).

The map in figure 10 was constructed by the inverse mass balance technique using the August 1984 water-table map (fig. 5). Because recharge rates calculated using the mapping technique are sensitive to hydraulic conductivity, calibration of the model to flow rates is necessary to ensure uniqueness of the solution. The model was calibrated to precipitation (that is, recharge cannot exceed precipitation), measured recharge rates at several points, stream flow, and basin yield (Stoertz and Bradbury, 1989).

Model calibration consisted of adjusting hydraulic conductivity within a reasonable range until simulated groundwater discharges agreed with field measurements of groundwater discharge to drainage ditches (Faustini, 1985) and basin yield (Holt, 1965). Holt (1965) estimated the average annual discharge for the Little Plover, Waupaca, and Big Eau Pleine Rivers to be equivalent to 26 cm/yr distributed evenly over the basin. During dry periods, the discharge was estimated to be 17 cm/yr. The model assumes a uniform hydraulic conductivity for the entire Buena Vista basin. The best model calibration used a hydraulic conductivity of 9×10^{-4} m/s, which is compatible with field measurements (table 1).

The computer-generated recharge/discharge map (fig. 10) generally corresponds to field data (fig. 9). The map suggests that, in a basin with a central discharging stream like the Buena Vista basin, discharge is focused along the center of the basin and recharge is distributed around most of the perimeter. Strong recharge areas tend to occur adjacent to strong discharge areas, which is consistent with Toth's (1963) concept of active local flow systems. The largest discharges occur along streams, as expected, because groundwater flow paths converge to discharging streams or wetlands.

Model simulations give an overall recharge rate of 33 cm/yr in recharge areas and an overall discharge rate of 46 cm/yr in discharge areas. These model-produced recharge and discharge values are sensitive to model discretization and cell spacing (Stoertz and Bradbury, 1989). Local flow systems, which account for much of the recharge and discharge within a ba-

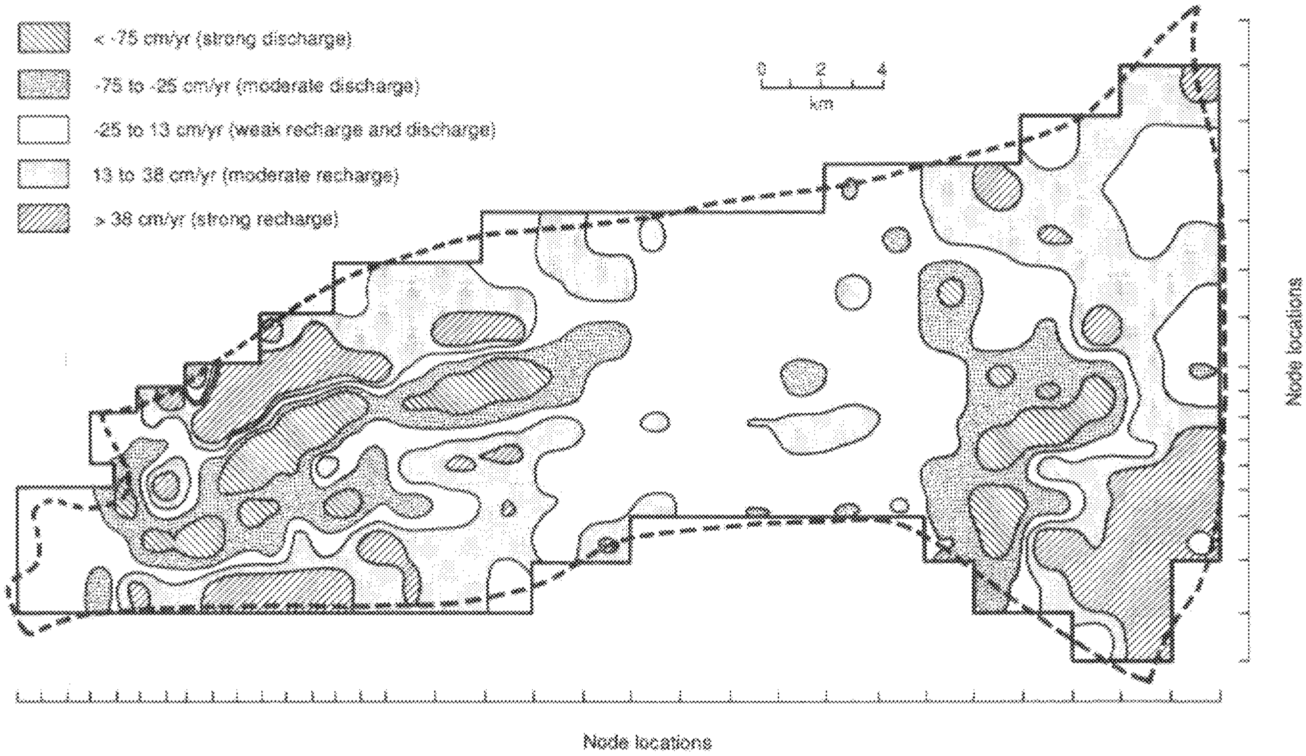


Figure 10. *Computer-generated recharge and discharge map of the Buena Vista basin (from Stoertz and Bradbury, 1989).*

sin, occur at all scales; by using a smaller cell spacing more local flow and, therefore, more recharge and discharge are accounted for.

The simulated recharge and discharge rates in the flat central basin are generally less than ± 20 cm/yr. These low rates may reflect the short flow paths of water in the central marshy area of the basin, where water enters and leaves the saturated flow system in less than 1 km. Water-level records for the central basin indicate that precipitation rapidly reaches the water table, but because the water table is shallow, and because the network of drainage ditches is large, most water discharges to drainage ditches soon after reaching the water table.

Significance of results

Taken together, the water-table map (fig. 5) and the recharge/discharge maps (figs. 9 and 10) are valuable for delineating groundwater flow patterns and the length of groundwater flow paths. One might expect, on the basis of Freeze and Witherspoon's (1967) models of thin, flat, areally extensive aquifers (such as the one in fig. 4b), that recharge would dominate the Buena Vista basin, and that discharge would be focused at the lower end near the constant-head (stream) boundary. In contrast, figures 9 and 10 show that groundwater flow in the Buena Vista groundwater basin is broken up into many small flow systems, and that recharge and discharge areas occur side by side at both ends of the basin. For example, water entering the aquifer along the regional groundwater divide discharges at the base of the Arnott moraine. Five sets of measurements of streamflow during periods of dry weather at several locations near the base of the moraine (Weeks and Stangland, 1971) show that a substantial amount of base flow originates in the headwater areas of the streams and drainage ditches, and that probably most groundwater recharged along the regional groundwater divide discharges there. Groundwater recharged in the central part of the basin discharges to the drainage ditches in the area; groundwater recharged in the area north of Buena Vista Creek discharges to Buena Vista Creek and drainage ditches near there; groundwater recharged west of the Buena Vista marsh discharges to Fourmile or Tenmile Creek. Groundwater discharge to the Wisconsin River and Nepco Lake originates locally, from adjacent recharge areas. Furthermore, the strongest discharge is not limited to the lower end of the basin but is found along the central part of the basin where surface drainage occurs. Recharge occurs not only at the upper end of the basin, as expected, but also along the sides.

Most of the groundwater in the Buena Vista basin probably travels along flow paths less than 5 km long. Regional flow paths of the type shown in figures 3 and 4b may not exist in the Buena Vista basin, but local and intermediate flow systems do occur. Most groundwater flow in the basin occurs in local flow systems, where groundwater moves from recharge areas to adjacent discharge areas. This observation is based on the water-table configuration (fig. 5), the distribution of recharge and discharge areas (figs. 9 and 10), and the abundance of tritium in groundwater samples (Bradbury, 1991). It is not necessarily true, however, that all the groundwater beneath an areally mapped discharge area will be intercepted and discharged within that area. Significant underflow can occur within deeper intermediate or regional flow systems.

Knowledge of the distribution of recharge and discharge areas is important for groundwater management and for delineation of wellhead-protection areas (Born and others, 1988). Groundwater contamination in a primary recharge area has the potential to penetrate deep into the aquifer and may eventually affect wells a long distance down the flow system. Groundwater contamination occurring in a discharge area or in a local recharge area does not have the same potential for widespread, long-term effects because groundwater originating in these areas is quickly discharged.

Conclusions and implications

The results of this study lead to several conclusions regarding groundwater flow and recharge in Wisconsin's central sand plain. The main conclusions are as follows:

- The aquifer system of the sand plain of central Wisconsin can be subdivided into smaller groundwater basins on the basis of topography, water-table configuration, and hydrogeologic boundaries. The Buena Vista basin is an example of one such self-contained groundwater basin.
- Groundwater flow in the basin is predominantly local. Groundwater flow from the regional divide to the Wisconsin River probably occurs only rarely within the basin. Most groundwater flow paths within the basin are less than 5 km long, although the basin itself is more than 30 km long.
- Relatively small hydrologic features, such as shallow drainage ditches, may have significant effects on groundwater flow in the basin, in some cases acting as fully penetrating boundaries to flow. Such ditches may have the ability to intercept contaminated groundwater moving laterally through the aquifer (Zheng and others, 1988a, 1988b).
- The areal distribution of groundwater recharge and discharge areas in the basin is complex. Although major mappable recharge areas occur, most groundwater flow paths are short, and many local recharge and discharge areas exist.
- On the basis of tritium data, the minimum age, or residence time, of groundwater in the Buena Vista basin ranges

from less than one year to more than 33 years. The oldest groundwater occurs in mapped discharge areas; the youngest, in mapped recharge areas.

- Our computer-generated recharge/discharge map generally corresponds to our map produced from field observations. The computer-aided mapping technique described here has promise for delineation of recharge and discharge areas in other parts of the central sand plain and similar areas of Wisconsin (Stoertz and Bradbury, 1989).

Application of results to other areas

A number of the results of this study can be generalized for application to the rest of the central sand plain and perhaps to other areas having similar geology. Localized groundwater flow in the study area is probably characteristic of the sand plain, and it is likely that the same kinds of hydrogeologic boundaries exist throughout the region.

The methods used to delineate recharge and discharge areas in this study can also be applied to other areas. Construction of a map such as that shown in figure 9 requires a large number of data points and a considerable expenditure of effort. However, if the computer modeling method (fig. 10) is used to guide data collection in the field, the amount of effort required to construct the map might be reduced considerably.

Caution must be used when applying the results of a study in one area directly to another area even in areas where the geology and topography of the two areas are generally similar. For example, from this study we concluded that continuous groundwater flow from the regional groundwater divide to the Wisconsin River does not occur within the Buena Vista groundwater basin. However, this conclusion may not be valid south of the study area, where an extensive fine-grained, lacustrine silt and clay deposit (the New Rome silt) occurs within the offshore lake sediment (Brownell, 1986). It is not known how this fine-grained unit affects the groundwater flow pattern, but it is quite probable that regional groundwater flow could occur beneath the silt and clay layer. Additional research is needed to define the thickness, extent, position, and hydraulic properties of this fine-grained lacustrine unit to assess its effects on groundwater flow patterns.

Implications for groundwater management

Information of the type contained in the map of recharge and discharge areas (fig. 9) can be an important management tool. For example, figure 9 can be used to identify priority areas for protection of groundwater quality at a basin-wide scale. It is more important to protect recharge areas than transitional or discharge areas because groundwater in recharge areas moves deeper into the flow system where, if contaminated, it might affect water-supply wells. Furthermore, it is most important to protect the central parts of recharge areas, near the crests of groundwater divides, because the longest groundwater flow paths originate there. When groundwater quality problems do occur, a map showing the distribution of recharge and discharge areas could be useful in identifying the source of the problem.

For managing groundwater basins in aquifers similar to those in the sand plain (unconfined, relatively homogeneous aquifers with shallow water tables and high hydraulic conductivity), the following approach is recommended:

- Construct a water-table map from existing water-level data (well data and information from earlier studies) as described by Blanchard and Bradbury (1987).
- Construct a transmissivity map using geologic maps and any other available

information such as pumping-test data, specific-capacity data, or grain-size distributions.

- Map all hydrogeologic features of the basin, such a springs, wetlands, streams, and major pumping centers.
- Generate a recharge/discharge map of the basin using a two-dimensional flow model with the water-table map and transmissivity map providing the necessary input data. Calibrate the model using surface-water flow data.
- Identify areas where the modeled pattern is ambiguous or requires resolution.
- Augment existing data with field work in key areas, as required.
- Identify, on hydrogeologic grounds, areas susceptible to contamination. This step will be subjective, and decisions will depend on the nature of the problem.
- In those areas identified as susceptible to contamination, determine the stratigraphy, depth to water, or other site-specific factors that affect recharge locally. The amount of effort required depends on the purpose of the evaluation.

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Appendix

Results of piezometer slug tests in the Buena Vista basin

This table summarizes the results of single-piezometer hydraulic conductivity (slug) tests performed in the Buena Vista basin. All tests were performed on piezometers (diameter 3.2 cm) with short screens located below the water table. Falling-head and rising-head tests were conducted by using a solid cylindrical slug of inert material to displace standing water in each piezometer bore. The slug was rapidly inserted or withdrawn, and water-level recoveries were measured using a pressure transducer connected to a strip-chart recorder. Data were analyzed using the method of Hvorslev (1951). Each test was repeated several times, and falling-head and rising-head results were averaged.

Piezometer	Twn	Rng	Sec	1/4 Sec	Depth to screen (m)	Hydraulic conductivity (m/s)
ALBT1	22N	9E	17	NWNESW	10.6	7.9×10^{-5}
ALBT2	22N	9E	17	NWNESW	16.7	2.4×10^{-4}
ALBT3	22N	9E	17	NWNESW	25.8	1.3×10^{-4}
ALBT4	22N	9E	17	NWNESE	40.3	1.0×10^{-4}
CHIC1	22N	8E	21	SWNWSW	2.7	5.8×10^{-5}
CHIC2	22N	8E	21	SWNWSW	9.4	2.0×10^{-4}
CHIC4	22N	8E	21	SWNWSW	34.9	6.4×10^{-5}
K86	22N	6E	21	SESENE	4.5	2.1×10^{-4}
K87	22N	6E	21	SESENE	8.7	9.8×10^{-6}
K88	22N	6E	22	NWNWSW	6.9	1.9×10^{-4}
K89	22N	6E	22	NWNWSW	13.6	8.8×10^{-5}
K103	22N	6E	27	NWNWNE	13.5	5.5×10^{-6}
K104	22N	6E	27	NWNWNE	8.7	1.2×10^{-4}
NURS1	22N	6E	32	NESENW	10.2	3.0×10^{-5}
NURS2	22N	6E	32	NESENW	14.1	7.6×10^{-4}
NURS3	22N	6E	32	NESENW	16.8	4.0×10^{-4}
NURS4	22N	6E	32	NESENW	19.5	2.6×10^{-6}
NW1A	22N	9E	17	NWNESW	9.8	2.1×10^{-4}
NW1B	22N	9E	17	NWNESW	14.8	8.2×10^{-4}
NW4B	22N	7E	25	NENESE	4.3	2.7×10^{-4}
NW4D	22N	7E	25	NENESE	16.4	8.2×10^{-4}
NW8A	22N	9E	15	NENWSW	15.0	4.9×10^{-4}
NW8B	22N	9E	15	NENWSW	34.7	4.0×10^{-4}
NW14	23N	9E	18	NENENE	13.3	1.7×10^{-5}
NW19B	21N	8E	15	NWNWNW	7.9	5.2×10^{-4}
NW24	23N	9E	17	NENENE	20.5	1.1×10^{-4}
NW26A	21N	7E	1	SESESE	1.9	2.3×10^{-4}
NW26C	21N	7E	1	SESESE	10.2	2.1×10^{-4}
NW27B	21N	9E	8	SESWSE	21.7	2.2×10^{-4}
NW29B	22N	7E	26	SESENE	6.6	7.9×10^{-4}
NW29C	22N	7E	26	SESENE	10.9	9.5×10^{-4}
NW32B	22N	7E	36	SWSWSW	6.2	4.3×10^{-4}
NW32C	22N	7E	36	SWSWSW	10.7	7.9×10^{-4}
NW33B	22N	7E	35	SWSWNW	4.1	4.3×10^{-4}
NW33C	22N	7E	35	SWSWNW	7.8	7.6×10^{-4}
NW33D	22N	7E	35	SWSWNW	11.5	9.1×10^{-4}
NW33E	22N	7E	35	SWSWNW	14.2	4.3×10^{-4}
NW33F	22N	7E	35	SWSWNW	22.0	4.6×10^{-4}
NW38B	22N	7E	34	NESENE	5.1	6.7×10^{-4}
NW38C	22N	7E	34	NESENE	8.7	7.6×10^{-4}
NW38D	22N	7E	34	NESENE	12.2	5.5×10^{-4}
NW48C	22N	7E	27	SESWNW	8.8	6.4×10^{-4}
NW48D	22N	7E	27	SESWNW	12.6	6.4×10^{-4}
NW48E	22N	7E	27	SESWNW	15.0	4.0×10^{-4}